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# Parametric Phase-sensitive Detector Using Two-cell SQUID

**Alexey Ustinov**

**Physikalisches Institut**
**Department of Physics**
**Karlsruhe, Germany D-76131**

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During this first reporting period evaluated the performance of two different microwave directional sensors based on two-cell SQUIDs. Two SQUID circuits with different values of McCumber parameter $\beta_c$ have been tested. Observed that best results can be obtained when the McCumber parameter $\beta_c \approx 1$. Found that the dc voltage of the proposed two-cell SQUID circuit can vary by 1.4 μV when the incoming angle θ varies 1°, which is a factor of 70 improvement to our previously obtained result. Also performed preliminary study of the basic properties of such parametric amplifier and its response to the phase difference between the two microwave signals. The further goal of this work would be to replace the single cell SQUID in the resonator by two cell SQUID and operate it by using two phase-shifted microwave pump signals. The transmission through the resonator measured at half the pump frequency should then be sensitively dependent on the phase shift between the two pumps.

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Research Report of the Project

# Parametric phase-sensitive detector

# using two-cell SQUID

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Ming He, Fengbin Song, and Alexey Ustinov

*Physikalisches Institut, Karlsruhe Institute of Technology, Germany*

August 2010

## ABSTRACT

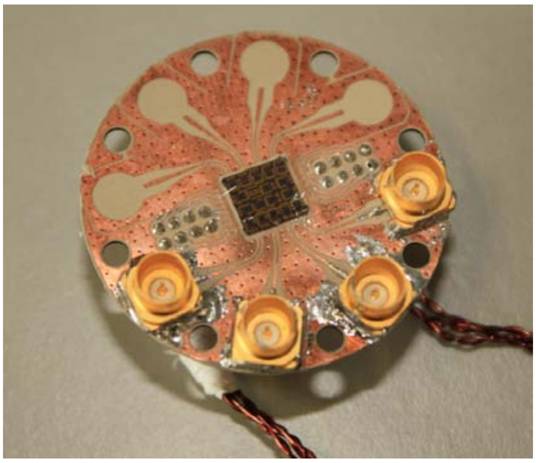
In this project, we intend to develop and investigate a sensitive microwave directional sensor based on a two-cell SQUID. In the first part this report, we report measurements of the current-voltage characteristics of the sensor based on 2-junction cells as a function of external magnetic field for different values of the McCumber parameter $\beta_c$. We also study the sensitivity of the sensor to the variations of the phase difference between two microwave signals coupled to the circuit. The optimum performance is found at $\beta_c \sim 1$. We have found that the *dc* voltage response of the two-cell SQUID with 2-junction cells reaches the value of 1.4 μV when the incoming angle $\theta$ changes by 1°, which is a factor of 70 improvement of our previously reported result with similar circuits based on two 4-junction cells. In the second part of the report, we report preliminary study of an alternative, microwave-based prototype readout scheme using a parametric amplifier based on a single-cell 2-junction SQUID embedded into a superconducting coplanar resonator. Basic properties of this parametric device are investigated and the parametric gain is obtained without using a cryogenic amplifier. Since the amplification depends on the phase difference of the pump microwave signals, it appears very promising to further study two-cell SQUIDs in a similar setting using a cryogenic amplifier close to the chip.


## Introduction

We proposed investigating a directional sensor based on very sensitive measurement of the phase shift between two microwave signals. Our approach employs two LC resonant modes of a two-cell SQUID, which can be operated in a passive way with or without applying *dc* bias currents on the SQUID by applying symmetric or antisymmetric *dc* fluxes. We have studied the response sensitivity of the device to small variations of the phase and/or amplitude of the microwave signals that are coupled to the two SQUID cells. Since the variation of the phase and/or the amplitude of the microwave signals between the two cells of the SQUID is a function of the angle of the incoming microwave, the two-cell based SQUID can be used to detect the incident angle of the microwave signal.

## 1. Experiments with dc biased SQUIDs

We have systematically investigated the current-voltage characteristics of the two-cell SQUID modulated with external magnetic fields for different values of the McCumber parameter $\beta_c$ . In addition, we have evaluated the sensitivity of the two-cell SQUID characteristics to the variation of the phase difference between two coupled microwave signals.



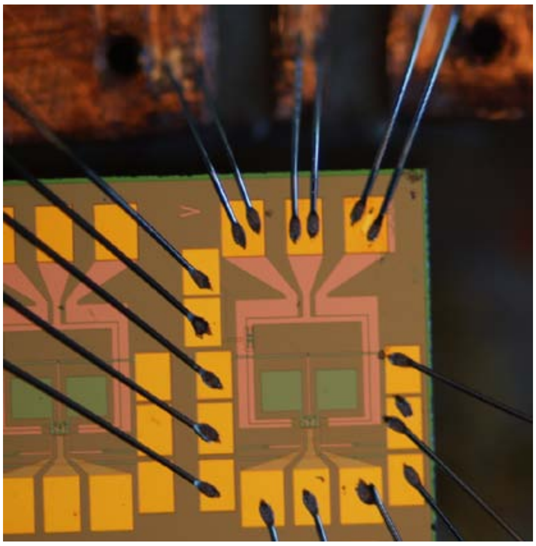
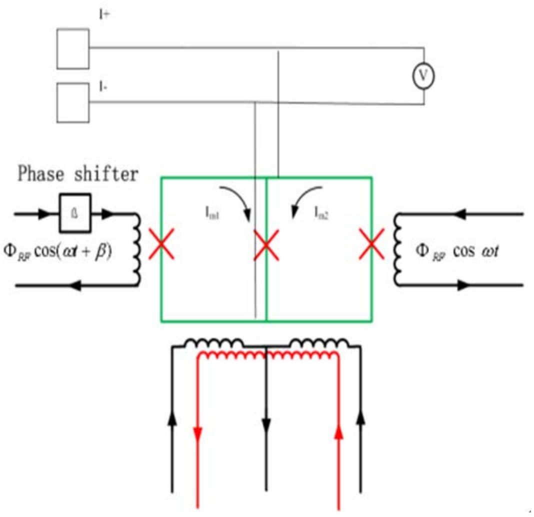


**Figure 1**. (a) . Photo of a 5×5mm$^2$ sample mounted on a sample holder suited for microwave measurements.

(b) . Image of one of the studied circuits bonded to the pads of the sample holder.

### 1.1 Experimental setup

A standard experimental setup for measurements at liquid helium temperatures was employed for testing the samples and evaluation of their parameters. The sample, mounted on a dip-stick using a suitable holder, remained in the vapor above the surface of liquid helium. This allows us to control the temperature of the sample in the range from 4.2 K to 6.5 K with the temperature stabilization accuracy sufficient for the presented experiments. The temperature of the sample was changed by lifting the sample to different positions above the surface of the liquid helium.



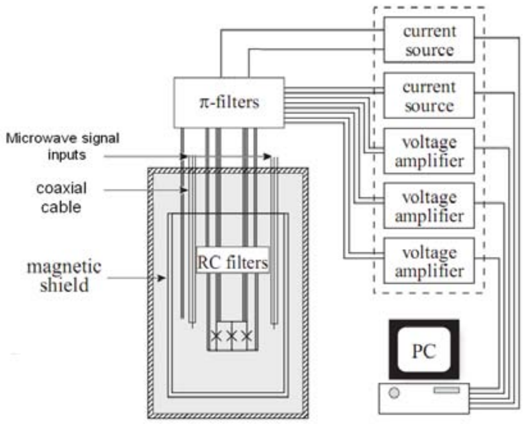




**Figure 2**. The sketch of the two-cell SQUID circuit.

**Figure 3**. The schematic view of the electronics setup of the measurements

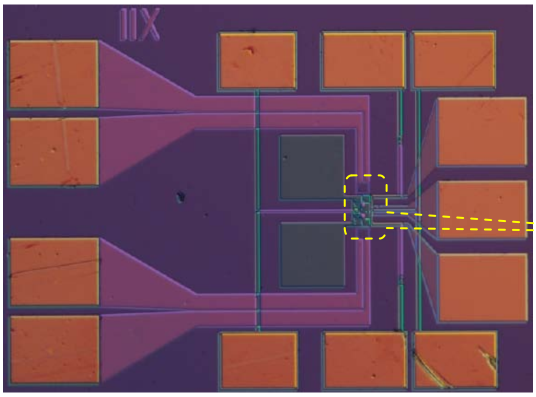
As shown in Figure 1, the sample is ultrasonically bonded to a sample holder through aluminum wires with a diameter of 25 μm. The symmetric low-pass RC filters (with ~15 dB cut-off frequency at ~1 kHz) on the sample holder shielded the circuit from external high-frequency electromagnetic interference. The sample is connected to the external analog electronics via twisted pairs of wires. To exclude the line resistances from the measurement, we use a standard four-point measurement technique. The shielding of the system from external dc magnetic fields is achieved through a cryoperm cylinder enclosing the bottom part of the dip-stick. The on-chip coils were used to apply the symmetric or anti-symmetric magnetic field to the sample. The microwave radiation was provided through the on-chip coupling circuits. Figure 2 shows the sketch of the two-cell SQUID circuit. Figure 3 displays the schematic view of the electronics setup that was employed for the measurements.

## 1.2 Experiment results and analysis

The investigated configuration of two-cell SQUID circuit consists of three Josephson junctions. Each junction is constituted by the lumped Nb/Al-$AlO_x$/Nb tunnel JJs. Niobium (Nb) is used as superconducting material with a critical temperature of $T_c$ = 9.2 K. The insulating barrier is made of aluminum oxide ($AlO_x$). In our design, the critical current density $J_c$ is 4.5 kA/$cm^2$ and the diameter of the junctions is 1.5 μm , which results in a critical current of ~ 80 μA.

We employed two ways to couple the microwave radiation signals to the two-cell SQUID circuit. One method is to use two microwave sources. The microwave is transmitted by two coplanar striplines on the chip. The phase difference can be adjusted directly by setting the microwave sources. An alternative approach employs only one microwave source. The microwave is transmitted by a coplanar waveguide and two coplanar striplines on the chip. The phase difference can be adjusted by the on-chip phase shifter embedded in one of the lines.

### 1.2.1 Circuits with two microwave input ports



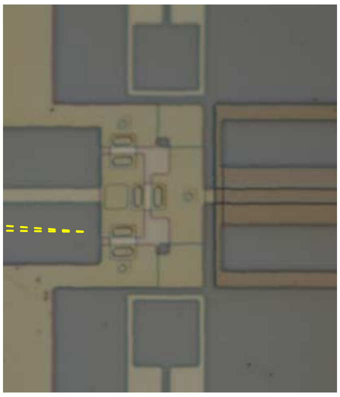


**Figure 4**. (a) Image of the two cell SQUID circuit with three JJs. The microwave radiations were provided by two microwave sources though two coplanar striplines.

(b) The insert showing the two-cell SQUID

Figure 4 shows the photograph of the circuit of a two cell SQUID using three JJs. The microwave radiation was provided by two microwave sources though two coplanar striplines. The coplanar striplines ended with two small coils which are placed nearby the two cell SQUID and used to couple the microwave signal to the SQUID, as shown in Figure 4(b). The dimension of the holes in this circuit is $4\times5.5\ \mu m^2$ and the distance between the two holes was ~ 45 μm.

In the following we show some experimental results of the microwave sensors based on two cell SQUID for different values of the McCumber parameter.

**Circuit with McCumber parameter $\beta_c \approx 1$**

In our first experiment, we study the case with the value of the McCumber parameter $\beta_c$ close to 1. The shunting junction capacitance is $C_p \approx 3.8$ pF, the normal resistance has a value of $R_n = 1\ \Omega$, and the junction plasma frequency is set to be $f_p \approx 40$ GHz.

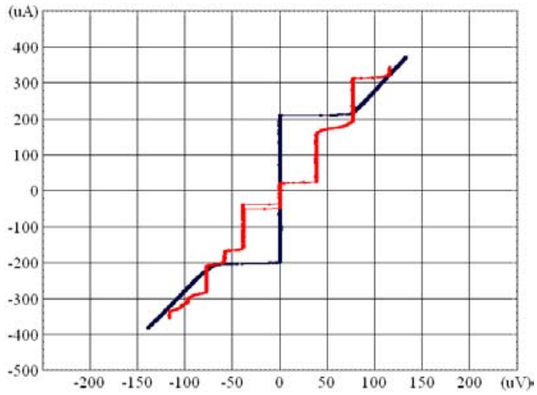



**Figure 5** The current-voltage characteristics of the two cell SQUID with (red line) and without (black line) microwave radiation. The frequency of the microwave radiation is 18.6 GHz. The x-axis and y-axis denote the voltage $V$ and the current $I$, respectively.

Figure 5 illustrates the $IV$ curve of the two-cell SQUID with (red line) and without (black line) microwave radiation. The frequency of the applied microwave radiation signal is 18.6 GHz. At the specified measurement temperature, the circuit has a critical current of $I_c = 75$ μA.

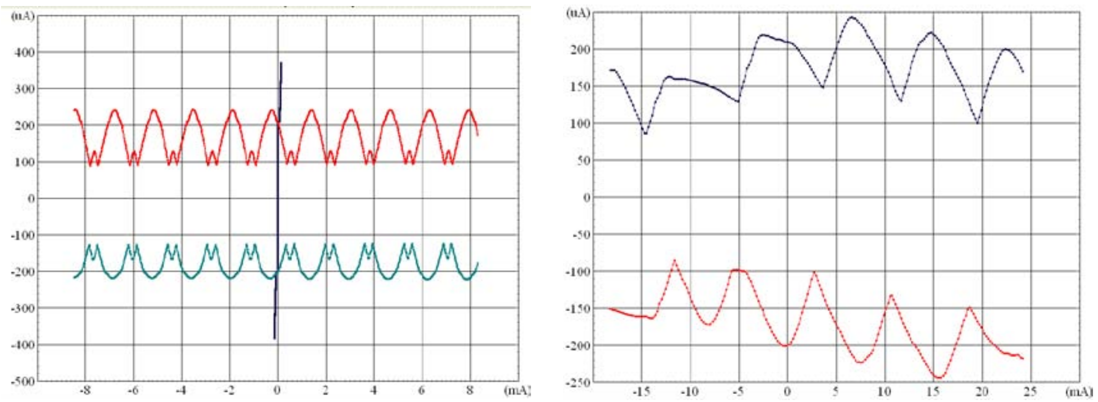



***Figure 6***. (a) The dependence of the circuit critical current on the symmetric dc magnetic flux. (b) The dependence of the critical current on the anti-symmetric dc magnetic flux.

Figure 6 shows the critical current of the two-cell SQUID versus the externally applied symmetric dc magnetic flux (a) and anti-symmetric dc magnetic flux (b) without microwave radiation.

As demonstrated in Figure 7 (a), when the bias current is set to the working point ***a***, a variation of the phase difference between two microwave signals produces a variation of the voltage from point ***a*** to point ***b***. By adjusting the external anti-symmetric and symmetric dc magnetic fluxes that are passing through the two cells of the circuit, we have found the most sensitive working position, which is shown in Figure 7 (b). From this figure, we can see that the dc voltage change at the steepest part of the curve has a

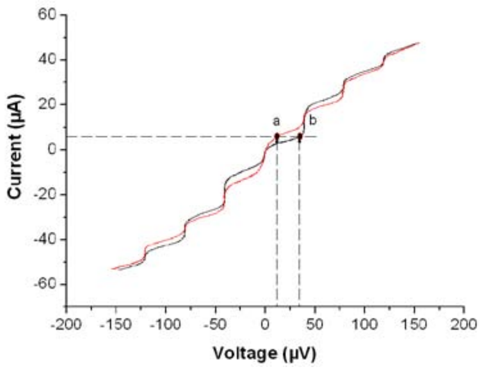
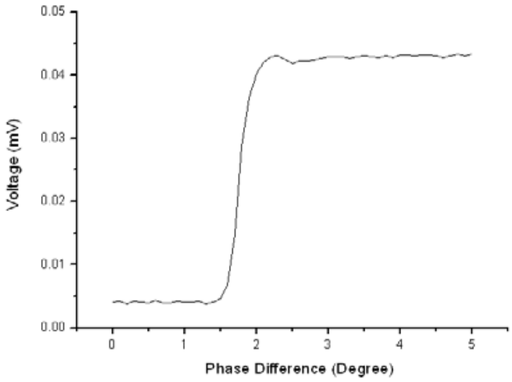



**Figure 7**. (a) The sketch of scheme to measure the voltage variation versus the phase difference between two microwave signals.




(b) The voltage variation versus the phase difference. The external anti-symmetric and asymmetric dc magnetic fluxes that are passed through the two cells of the circuit were adjusted at the most sensitive working point. The frequency of the microwave is 18.6 GHz.

variation of ~ 130 μV induced by one degree of the microwave phase difference, which means

$$\frac{\Delta V}{\Delta \beta} = 130\,\mu\text{V/degree}$$

The directional accumulation of the phase difference introduced by a hypothetical incident microwave signal is illustrated in Figure 8. Assuming that the cells are placed in a free space, the phase difference $\beta$ between the signals received by the two cells can be written as

$$\beta = \frac{2\pi d \sin\theta}{\lambda} \quad ,$$

where $\theta$ denotes the angle of the incoming signal, $d$ is the distance between two cells of the SQUID and $\lambda$ is the wavelength of the incoming microwave radiation. In our experiments, the frequency of the incoming microwave signal is 18.6 GHz and $d$ = 45 μm. As a result, when the incoming angle $\theta$ varies by 90°, phase difference will

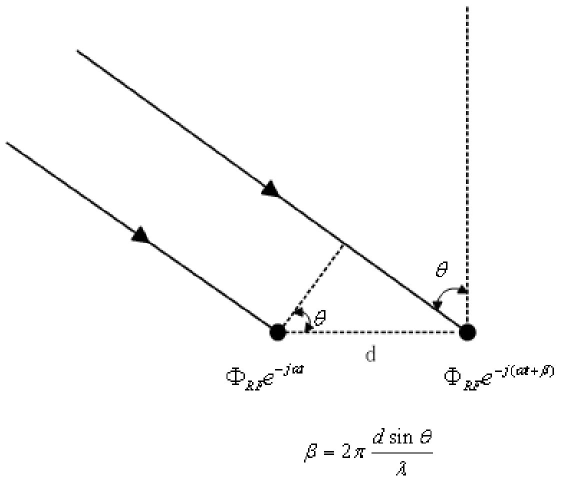



**Figure 8**. The relationship between the incoming angle θ and the phase difference $\beta$.

acquire about 1°. Therefore, the voltage changes by ~ 1.4 μV as the incoming angle θ is varied by 1°, which can be written as

$$\frac{\Delta V}{\Delta \theta} = \frac{\Delta V}{\Delta \beta}\frac{1^\circ}{90^\circ} = 1.4\,\mu\text{V/degree}\,.$$

We have anticipated that we may find some working points where the voltage change is irregular (close to onset of chaos) and may be more sensitive to the phase difference of the microwave radiation signals as we adjust the external antisymmetric or symmetric dc magnetic fluxes that pass through the two cells of the circuit and the frequency of radiation microwave signal. Unfortunately, the experiment results that we had measured so far do not support this expectation. The voltage change induced by the phase difference of the microwave radiation signals is not as sensitive as we have anticipated for the chaotic regime (as shown in Figures 9 and 10). But further works should be done before we confirm the phenomena.

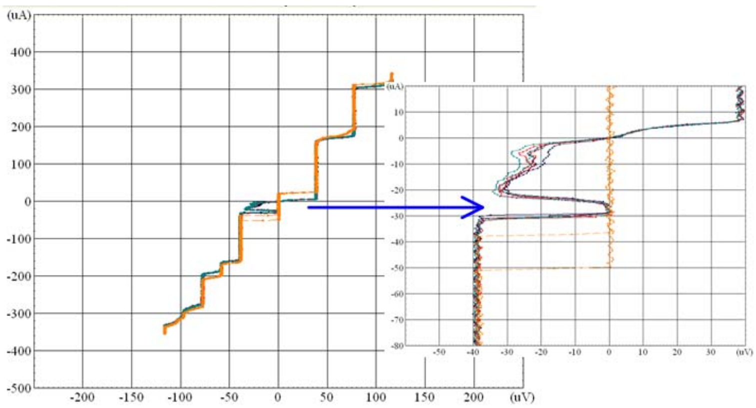


**Figure 9**. The current-voltage characteristics of the two-cell SQUID under the radiation of two microwave signals for different values of the phase differences $\beta$. The frequency of the microwave radiation is 18.6 GHz.

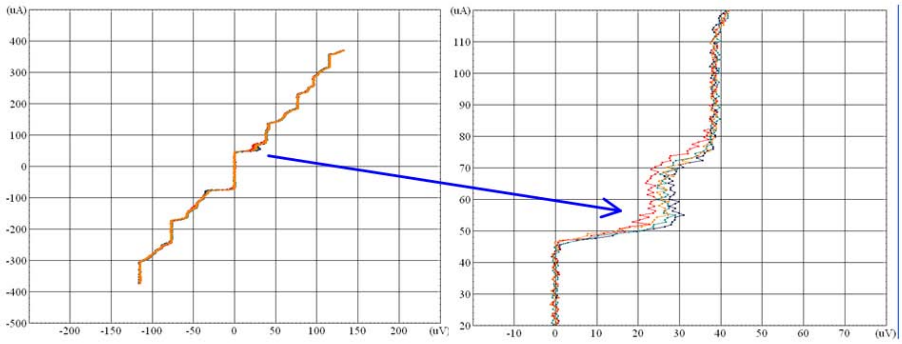


**Figure 10**. The current-voltage characteristics of the two-cell SQUID under the radiation of two microwave signals for different values of the phase differences $\beta$ from 8°to 15°. The frequency of the microwave radiation is 18.5 GHz.

## Circuit with the McCumber parameter $\beta_c$ >>1

In this section, we consider the design with the value of the McCumber parameter much larger than 1, i.e. $\beta_c$ >>1. The junctions are shunted by capacitors with $C_p \approx 3.8$ pF and there is no shunted resistance. The normal resistance of the junctions is $R_n =$ 25 Ω, and the plasma frequency is $f_p \approx 40$ GHz.

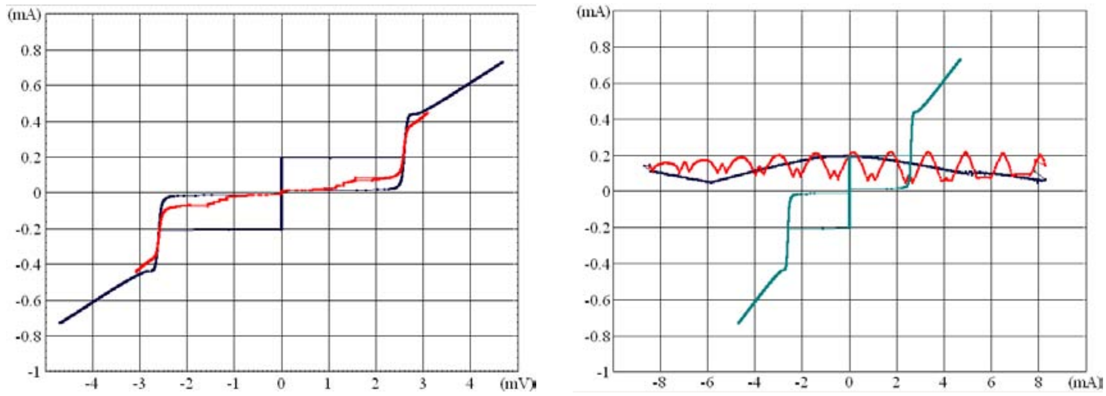


**Figure 11**. (a) The current-voltage characteristics of the two cell SQUID with (black line) and without (red line) microwave radiation. The frequency of the microwave radiation is 19.38 GHz.

(b) The dependence of the critical currents of the two-cell SQUID on the externally applied symmetric (red line) and anti-symmetric (black line) dc magnetic flux.

Figure 11 (a) shows the current-voltage characteristics of the two cell SQUID with and without microwave radiation. The frequency of the microwave radiation is 19.38 GHz. Figure 11 (b) displays the dependence of the critical currents of the two-cell SQUID on the externally applied symmetric and anti-symmetric DC magnetic flux. However, no matter how we adjusted the external anti-symmetric or symmetric dc magnetic fluxes through the two cells of the circuit and the frequency of radiation microwave signal, we have not found any working points where the voltage change is highly sensitive to the phase difference between the microwave radiation signals.

### 1.2.2 The circuit with one microwave signal input port and an on-chip phase shifter

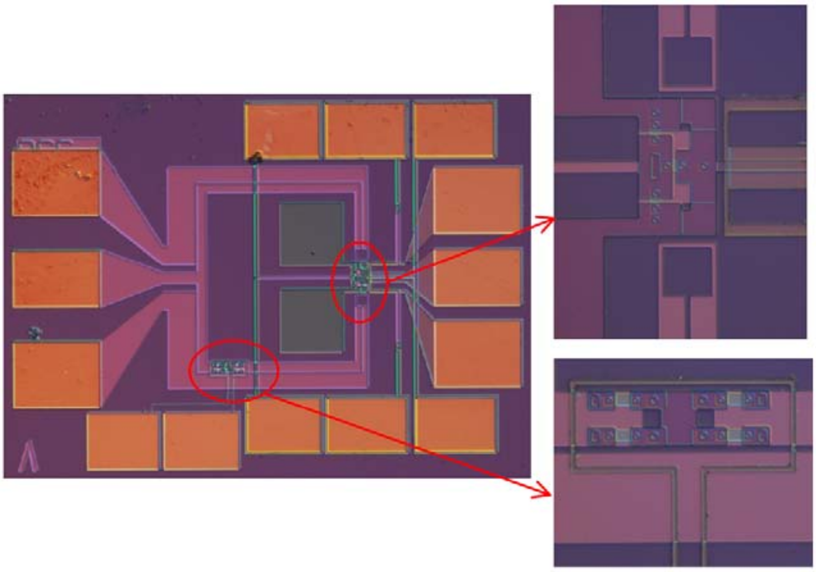


**Figure 12**. Optical image of the two-cell SQUID circuit with three JJs. The top-right insert is the enlarge picture of the two cell SQUID. The down-right insert is the enlarge picture of an on-chip phase shifter.

For testing this circuit, only one microwave source was used. The microwave signal is firstly transmitted by a coplanar waveguide and is then divided in two equal signals through two coplanar striplines on the chip. The idea of this design was to adjust the phase of one of the lines by using the phase shifter tunable by magnetic flux applied through a on-chip coil. Figure 12 shows the photograph of our design. The top-right insert is the enlarge picture of the two cell SQUID. The down-right insert is the enlarge picture of an on-chip phase shifter, which consists of two SQUIDs connected in series. The shunted capacitor of the junctions is $C_p \approx 3.8$ pF, the normal resistance is $R_n$=1.8 Ω, plasma frequency is $f_p \approx 40$ GHz and the McCumber parameter $\beta_c \approx 3$. The dimension of the holes in this circuit is 4×5.5 μm$^2$. The distance between the two holes is ~ 45 μm. Figure 13 shows the *IV* curve of the two cell SQUID. The critical current $I_c$ is ~ 240 μA.

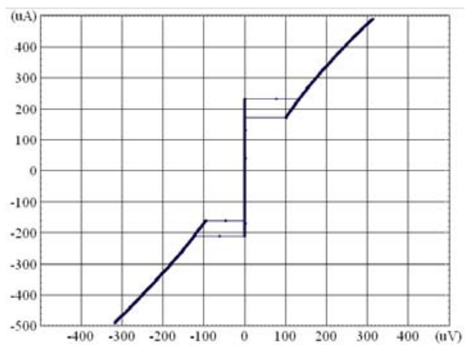



**Figure 13**. The current-voltage characteristics of the two cell SQUID. The x-axis and the y-axis denote the voltage and the current, respectively.

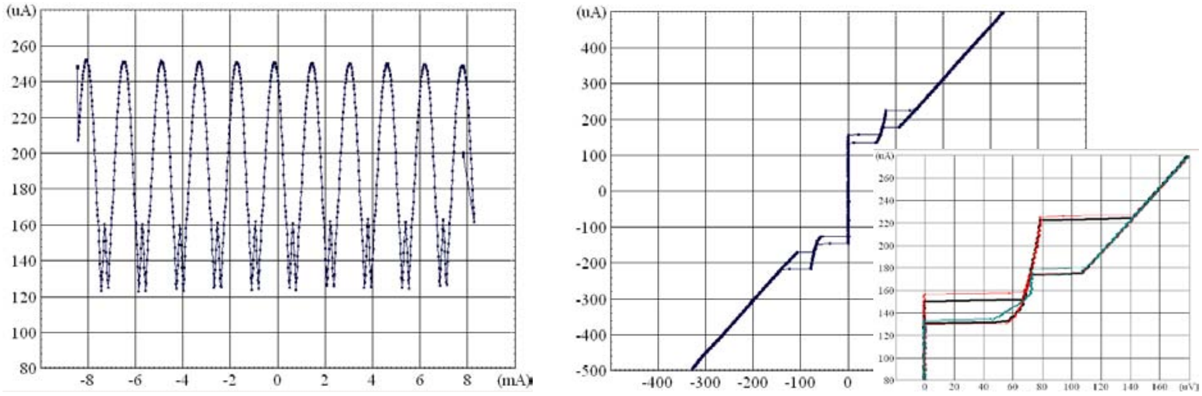



**Figure 14**. (a) The dependence of the critical currents of the two cell SQUID on the externally applied symmetric dc magnetic fluxes. The x-axis is the dc magnetic flux and the y-axis is the critical current.

(b) The current-voltage characteristics of the two cell SQUID applied with certain external symmetric dc magnetic flux. The x-axis is the voltage and the y-axis is the critical current. The down-left insert shows the current-voltage characteristics of the two cell SQUID with different external symmetric dc magnetic fluxes.

Figure 14 (a) shows the dependence of the critical currents of the two cell SQUID on the externally applied symmetric dc magnetic fluxes. Figure 14 (b) illustrates the current-voltage characteristics of the two cell SQUID with certain external symmetric dc magnetic flux. The step in the figure denotes the resonating frequency of the two cell SQUID, which is ~ 35 GHz. The down left insert shows the current-voltage characteristics of the two cell SQUID with different external symmetric dc magnetic fluxes.

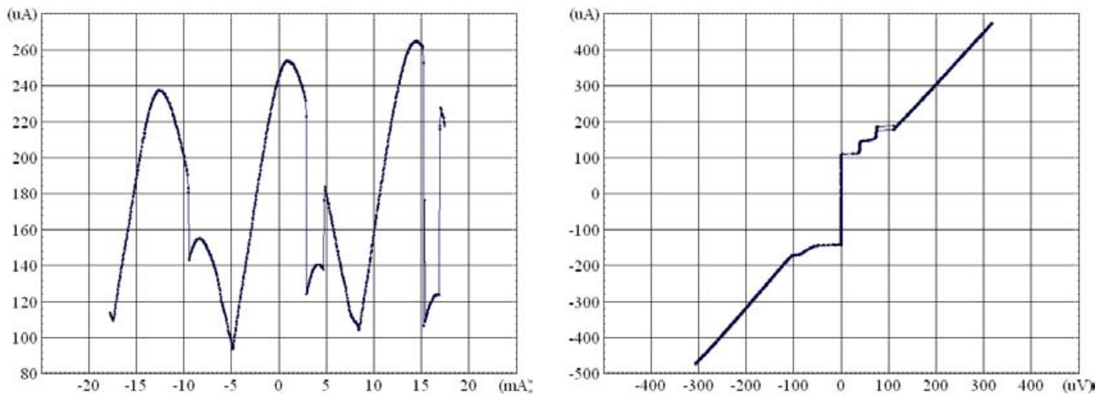



**Figure 15**. (a) The dependence of the critical currents of the two cell SQUID on the externally applied anti-symmetric dc magnetic fluxes. The x-axis is the dc magnetic flux and the y-axis is the critical current.

(b) The current-voltage characteristics of the two cell SQUID with certain external anti-symmetric dc magnetic flux. The x-axis is the voltage and the y-axis is the critical current.

Figure 15 (a) shows the dependence of the critical currents of the two cell SQUID on the externally applied anti-symmetric dc magnetic fluxes. Figure 15 (b) illustrates the current-voltage characteristics of the two cell SQUID with certain external anti-symmetric dc magnetic flux. The steps in the figure denote the resonating frequency of the two cell SQUID with anti-symmetric dc magnetic fluxes, which are ~ 18.9 GHz and ~ 35.7 GHz.

We tested the variation of the microwave signal using the designed on-chip phase shifter. The measured response of the transmitted microwave to the magnetic flux applied through the phase shifter was found to be very small. We believe that this experiment did not work out properly due to the smallness of the Josephson inductance compared to the inductance of the line. Future improvement of this approach may rely on working at a frequency close to the LC-resonance in the phase-shifter SQUID, similar to that shown in Figs. 14(b) and 15(b). This would in turn require shunting the phase shifter junctions by large capacitances chosen to shift the SQUID resonance frequency to sub-20 GHz range.

## 2. Experiments with SQUID embedded in a resonator

Microwave biased SQUIDs can serve as parametric amplifiers employing the nonlinearity of Josephson junctions [1]. To improve the sensitivity, a SQUID can be embedded into a superconducting coplanar waveguide resonator [2]. We have performed preliminary study of the basic properties of such parametric amplifier and its response to the phase difference between the two microwave signals. The further goal of this work would be to replace the single cell SQUID in the resonator by two cell SQUID and operate it by using two phase-shifted microwave pump signals. The transmission through the resonator measured at half the pump frequency should then be sensitively dependent on the phase shift between the two pumps.

### 2.1 Experimental setup

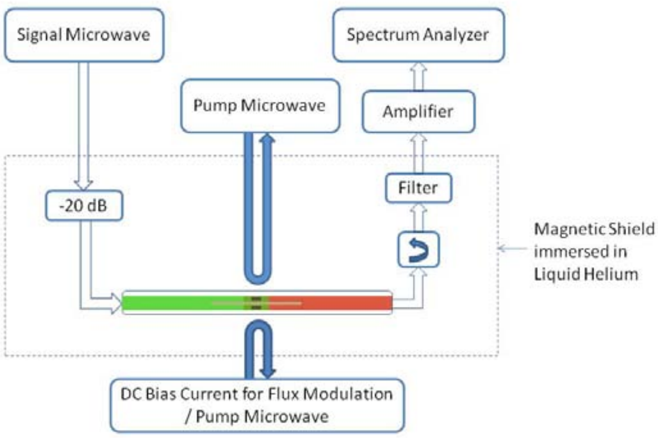



**Figure 16**. Schematic of RF measurement system.

Our microwave transmission measurement setup is shown in Figure 16. The sample, mounted on a dip-stick, was protected from external dc magnetic fields with a cryoperm magnetic shield. Microwave signal to the SQUID in the resonator was supplied by a source through an attenuator of -20 dB. The microwave was fed into the coplanar resonator by a coplanar capacitance of 9 fF, and corresponding response was coupled to a superconducting output transmission line by another capacitance of the same value. The signal transmitted through the resonator was fed into a spectrum analyzer through a circulator, a low-temperature filter and a room-temperature amplifier of +28 dB gain. The dc bias for flux modulation of the SQUID and external pump microwave were applied by two separate coplanar on-chip coils. The sample surrounded with the magnetic shield was immersed in liquid helium and thus the following measurements were performed at 4.2 K. The layout of the sample bonded to the sample holder through aluminum ribbon (its enlarged width compared to boding wire ensures lower inductance and thus lower impedance at microwave frequencies), is shown in Figure 17.

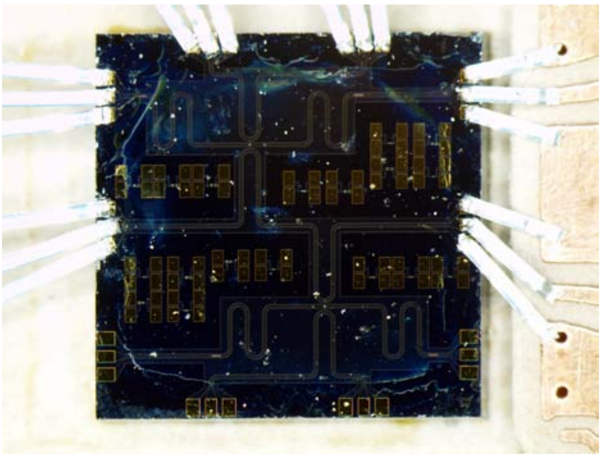


**Figure 17**. Photo of the sample ribbon-bonded to the sample holder.

### 2.2 Experiment results and analysis

Once the microwave bias signal frequency $f_b$ is set close to the resonant frequency of the coplanar resonator, the output response signal can be amplified under pump microwaves coupled into the SQUID at a frequency of $f_p = 2f_b$. When working with two pumps coupled to a two cell SQUID, the amplification should depend on the phase difference between the pump microwaves. In this way the two cell SQUID may serve as a microwave directional sensors for the pump microwaves.

#### 2.2.1 Basic properties of the parametric amplifier

The resonant frequency of the coplanar resonator is dependent on the length of the superconducting transmission line between the two coupled coplanar capacitances. With a network analyzer, the resonant frequency was confirmed to be 8.985 GHz and the quality factor Q of the resonator was measured to be equal to 107 (see Figure 18).

Near this resonant frequency, the transmitted signal was amplified by applying the pump microwave at the twice signal frequency, as shown in Figure 19. The power of the pump microwave $P_\mathrm{p}$ should be much larger than that of the bias signal $P_\mathrm{b}$. Here, we used $f_\mathrm{b}$ = 9 GHz, ,$f_\mathrm{p}$ = 18 GHz, $P_\mathrm{b}$ = -150 dBm, $P_\mathrm{p}$ = -35 dBm. The amplification gain, which is defined as the difference of the signal peak values with and without pump microwaves, was measured under these conditions to be about 6 dB.

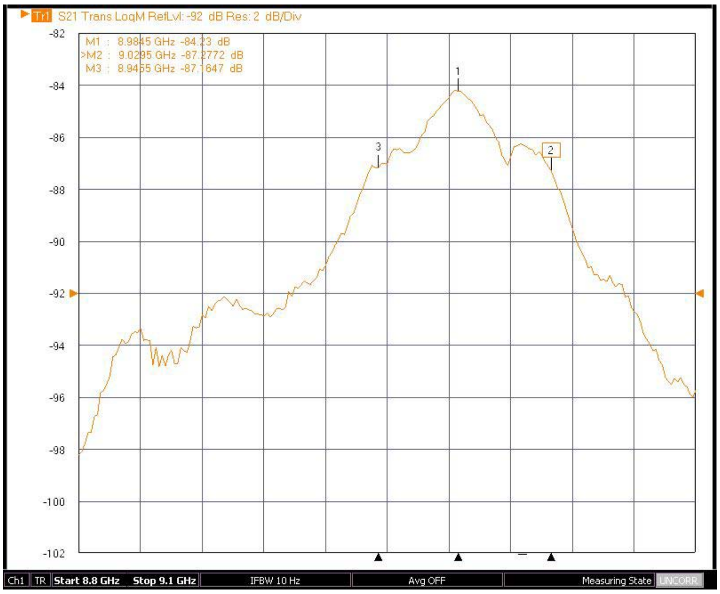



**Figure 18**. Spectrum of the superconducting coplanar waveguide resonator.

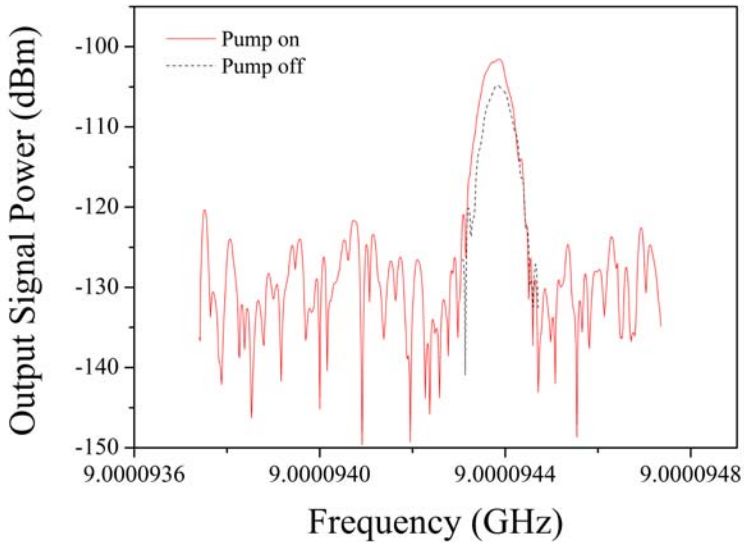



**Figure 19**. Amplified output signal under the pump microwave.

The influence of the phase difference between the microwave signal bias and the pump microwaves on the amplification gain was investigated, as shown in Figure 20. As expected, it shows a periodic dependence with a period of 2π. At certain phases, the peak value was lower than the pump-off level, and the gain was negative, which is often referred as ‘deamplification’.

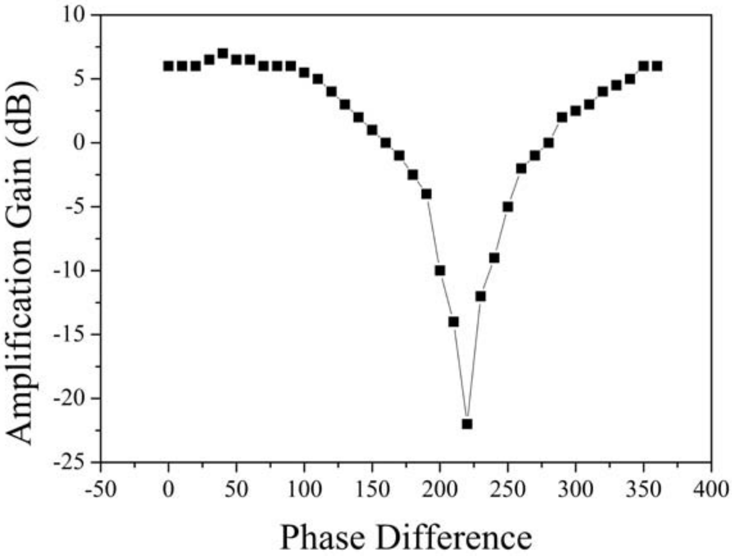



**Figure 20**. Gain as a function of the phase difference between the signal $f_b$ and the pump $f_p = 2f_b$.

To investigate the dependence of the amplification gain on the magnetic flux modulation, dc bias current was applied to the other coplanar coil to adjust the static magnetic field in the SQUID loop. For different pump power $P_\mathrm{p}$, the influence of the flux was various. When the $P_\mathrm{p}$ was larger than -10 dBm, the gain was almost independent of the flux modulation. We suppose that Josephson junctions in the SQUID were overdriven (to the normal resistive state) in this case. When the $P_\mathrm{p}$ was around -20 dBm, the influence of the flux was shown in Fig. 21. The critical current of the SQUID was modulated by the flux. Even if the pump power $P_\mathrm{p}$ was fixed, the junctions could be overdriven at certain flux values. When the $P_\mathrm{p}$ was smaller than -30 dBm, the influence of the flux modulation was hardly noticeable.

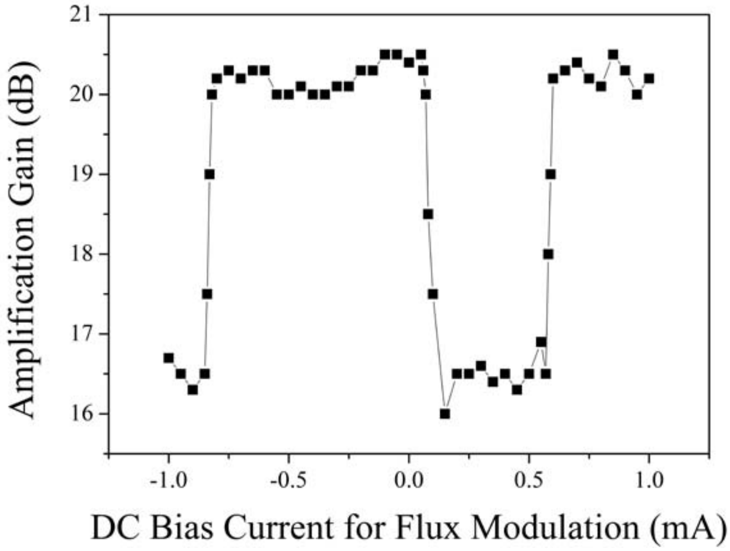



**Figure 21**. Gain as a function of the magnetic flux.

### 2.2.1 Performance dedicated for the microwave directional sensing

To operate the embedded SQUID as a microwave directional sensor, two synchronized pump microwaves at $f_p = 2f_b$ need to be applied to the coplanar coils located on two sides of the coplanar resonator. We have performed this kind of measurement. The dependence of the amplification gain on the phase difference between two pump microwaves was investigated, as shown in Figure 22. As it can be expected for $f_p = 2f_b$, the period of the dependence was $4\pi$. At the most sensitive points, we had a variation of ~ 0.15 dB induced by one degree of the phase difference.

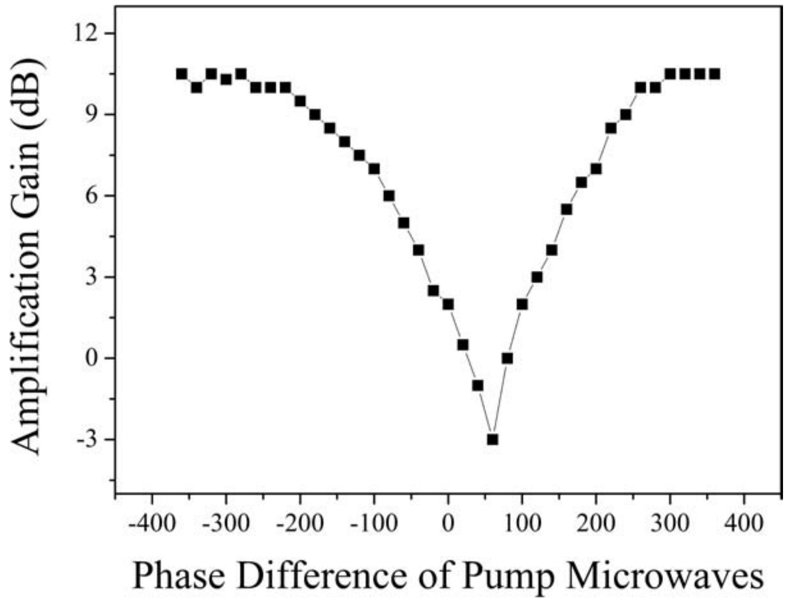



**Figure 22**. Gain as a function of the phase difference between two pump microwaves.

## Conclusions

We have evaluated the performance of two different microwave directional sensors based on two-cell SQUIDs. Two SQUID circuits with different values of McCumber parameter $\beta_c$ have been tested. We have observed that best results can be obtained when the McCumber parameter $\beta_c \approx 1$. We have found that the dc voltage of the proposed two-cell SQUID circuit can vary by 1.4 μV when the incoming angle θ varies 1°, which is a factor of 70 improvement to our previously obtained result.

We have also performed preliminary study of the basic properties of such parametric amplifier and its response to the phase difference between the two microwave signals. The further goal of this work would be to replace the single cell SQUID in the resonator by two cell SQUID and operate it by using two phase-shifted microwave pump signals. The transmission through the resonator measured at half the pump frequency should then be sensitively dependent on the phase shift between the two pumps.

## References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